TITLE: On the Parasitic Mass of Launch Packages for Electromagnetic Guns

ON THE PARASITIC MASS OF LAUNCH PACKAGES FOR ELECTROMAGNETIC GUNS

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Conventional gun and projectile design methodology has evolved over the last 50 years to a state where computer generated models can safely predict shot behaviour, from loading into the gun through to target impact. Long rod kinetic energy (KE) projectile packages with parasitic mass ratios (PMR) below 0.3 are becoming the norm for the conventional gun launched environment. In contrast, electromagnetic (EM) gun and projectile design methodology is far from mature, given the relative youth of the technology (<15 years), the increased complexity of the governing physics and the scarcity of major programmes addressing the area. The Defence Evaluation and Research Agency (DERA) is investigating EM gun technology on behalf of the United Kingdom Ministry of Defence, as a possible contender for the direct fire role in a future armoured land vehicle. One of many key issues is to establish the bounds on the PMR for long rod EM KE packages. Initial UK designs of EM KE launch package have been of the circular bore, 'base-push', type where the armature is positioned behind the projectile. A comprehensive programme has resulted in a good understanding of the PMR bounds for this configuration. More recent studies have focussed on circular bore, 'mid-ride' concepts, where the armature is situated near the mid-point of the shot and there is potential to attain further reductions in PMR. The paper presents an overview of the UK KE launch package studies together with a more detailed assessment of the expected PMRs.

INTRODUCTION

The UK Defence Evaluation and Research Agency (DERA) has an extensive capability for the design of conventional gun launched armour piercing, fin-stabilised, discarding sabot (APFSDS) kinetic energy anti-tank projectiles. The capability encompasses internal ballistics prediction, penetrator materials technology, sabot design, shot/barrel interaction modelling, aeroballistics and accuracy, and terminal effectiveness assessment via hydrocode modelling. The theoretical capability is reinforced with trials programmes, both strength of design and armour defeat, such that an extensive body of experimental data has been collected.

As implied above, maximising the performance of a KE penetrator to defeat a threat armour is reliant on a 'systems' approach - the terminal effectiveness being dependent on an array of system parameters which interact in a complex fashion. For example, in a conventional gun, the propellant charge requirement must be optimised with respect to the gun type (chamber volume and operating pressure) and the shot mass to achieve the best muzzle velocity.

A kinetic energy long rod is launched with a sabot, which fills the space between the rod and the bore, converting combustion pressure into a distributed force along the length of the rod. The sabot is discarded at the muzzle and constitutes parasitic mass. The parasitic mass ratio (PMR, the mass of discarded components to total shot mass) has therefore become a key indicator of shot design efficiency. Typically a PMR of about 0.45 is possible for a depleted uranium (DU) rod with an aluminium alloy sabot of 'saddleback' configuration[1]. This figure can be reduced by changing to a 'double-ramp' configuration[2], by using high strength rod materials, or by using lightweight sabots. A fibre reinforced plastic (FRP), double-ramp sabot can offer PMR values of around 0.3. However, to take advantage of a lower PMR requires considerable interaction with the remainder of the system: a longer rod with a double-ramp sabot needs a suitable combustion chamber and the necessary stowage; a higher muzzle velocity, attributable to lower shot mass, needs an optimised charge.

Current UK interest in the emerging electromagnetic gun technology is as a contender for the main armament of a future land combat system. Given the military need for more readily deployable forces (the US FCS and the UK FRES initiatives), great attention is being focussed on air-portable armoured vehicles with a robust capability to defeat enemy threats (Ref 1). EM gun technology has many attractive features, including:

- Low recoil (of critical concern for a light vehicle).
- Improvements in survivability by elimination of energetic materials from the vehicle.
- Reduction in logistic drag by elimination of energetics from the supply chain.
- Enhanced target defeat by providing hypervelocity launch velocity.

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[1] 'Saddleback' refers to the sabot configuration where the main pressure bulkhead/obturator is near the back of the shot. Most of the rod is launched in compression and only a small section of rod carrying the fin is subjected to tensile stress.

[2] 'Double-ramp' is the sabot configuration where the main pressure bulkhead is about half way along the rod. A short saddleback section is complimented by a rear ramp subjected to combustion pressure. More of the rod is launched in tension than in saddleback designs.

DERA has been researching electromagnetic launch technology on behalf of UK MoD for the last 10 years, drawing on its conventional gun expertise and enhanced by investment in large scale EM launch facilities, principally at Kirkcudbright (which is the only facility in the world capable of launching EM projectiles and flying them out to long ranges). A systems approach has been taken and, as a consequence, significant advances in EM launch technology have been achieved (Refs 2, 3, 4).

Reducing the parasitic mass ratio for an EM gun launched projectile is a significantly greater challenge than for a conventional projectile. The EM projectile must fulfil an additional function, that of conducting a high electrical current across the rails, which implies the need for metallic components (thereby increasing the PMR significantly). In the light of this, a PMR goal of 0.5, somewhat higher than for conventional projectiles, has received common acceptance by the EM projectile community (eg Ref 5). The current paper describes the UK progress with large calibre EM projectile designs with particular emphasis on minimising the PMR towards the goal of 0.5.

One of many tools which has been developed to aid the study has been an analytical model for estimating the PMR, taking into account the sabot/penetrator material properties and the influence of the armature mass. This tool is described in the first section. Next, the UK programme in EM gun projectiles is presented in more detail, followed by design proposals for EM projectiles with reduced PMR. Details of relevant firings of experimental armatures is complimented by the results of EM modelling. Finally the use of alternative bore shapes, other than round, is discussed in terms of the impact on sabot designs.

EM GUN PROJECTILES - OVERVIEW

Projectile Configurations

As with conventional guns, EM gun projectiles have two principal configurations: base-push and mid-ride. In a base-push design, the armature pushes the shot from behind. This is similar in concept to the saddleback design of conventional rounds.

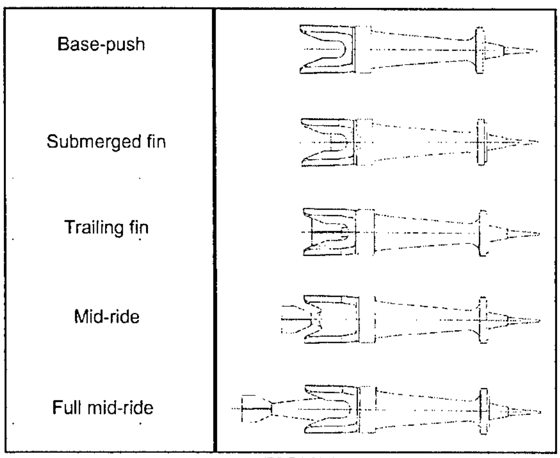


FIGURE 1

The mid-ride design has the armature situated (approximately) mid-way along the penetrator, and the sabot possesses both saddleback and rear ramps. The key difference between this concept and the double-ramp conventional shot is that the rear ramp of the EM projectile is not subjected to combustion pressure. The evolution from base-push to full mid-ride encompasses a range of design configurations depicted in Fig 1.

The initial UK work was performed with circular-bore, base-push projectiles with separate armatures to allow read-across of design data from conventional rounds and independent armature development. The design principles used for EM projectiles were similar to those for powder gun projectiles. The ratio of penetrator length to penetrator diameter (L/D) for conventional rounds is typically in the range 15 to 35. Similar values of L/D have been considered for UK EM gun projectiles.

Parasitic Mass Ratio Estimation

It is possible to derive an analytical expression for the parasitic mass ratio of an idealised base-push projectile subjected to axial acceleration. The following assumptions are necessary:

- The axial strain in the penetrator is equal to the axial strain in the sabot (Ref 6).
- The penetrator of length L has an overhang equal to L_0 at the front of the projectile which is not supported by the sabot.
- The penetrator cross-sectional area, A_0, is constant along its length.
- The stress in the penetrator, when supported by the sabot, is constant and equal to the stress at the base of the front overhang.
- The stress states in the rod and sabot are due only to the effect of body forces arising from axial acceleration.

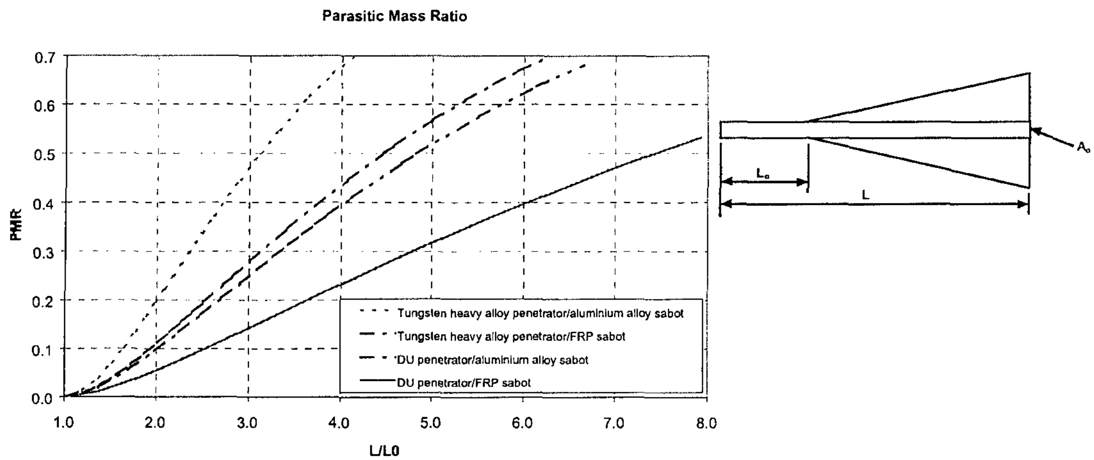


FIGURE 2

Fig 2 illustrates how the projectile PMR varies for idealised constant stress sabots as a function of the ratio L/L_0 (penetrator length/penetrator front unsupported length) considering different rod and sabot materials.

The relationships embodied in Fig 2 are for wedge-shape, base-push sabots of circular cross-section. By symmetry about the basal plane, they are also applicable to mid-ride sabots with penetrator length 2L and front and rear L_0 overhangs. At a typical value of $L/L_0 = 4$, the use of a fibre reinforced plastic for the sabot instead of aluminium alloy reduces the PMR by 0.24 for a tungsten alloy penetrator and 0.15 for a depleted uranium rod. Changing from a tungsten heavy alloy penetrator to a DU penetrator is slightly more effective, with a reduction in PMR of about 0.29 for an aluminium alloy sabot, and 0.2 for an FRP sabot. The PMR is not a function of penetrator length to diameter (L/D) ratio based on this formulation. The influence of L/D is only apparent in real designs because the front and rear bore riders must extend from the penetrator to a fixed bore diameter.

These calculations illustrate trends in PMR considering different rod and sabot materials whilst deliberately excluding the mass of the armature. Adding an armature to a base-push shot significantly increases PMR as discussed below.

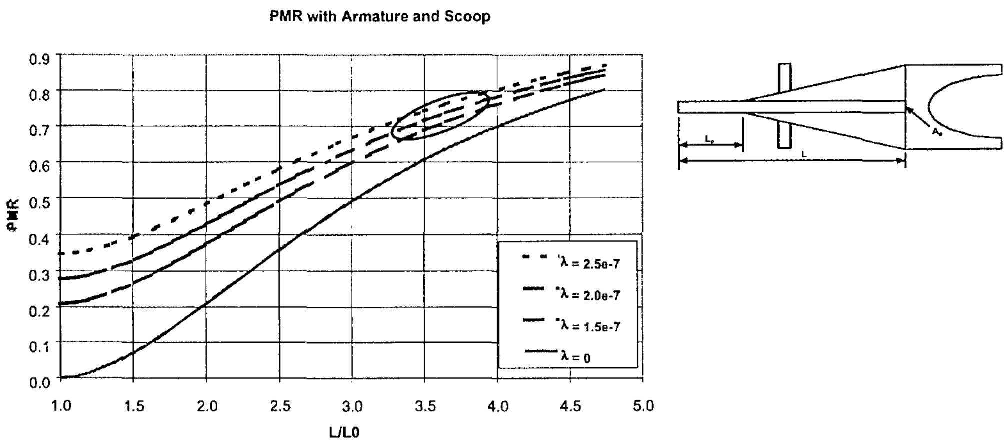


FIGURE 3 - Aluminium alloy sabots - $\lambda = V/(L' \times g)$ in SI units

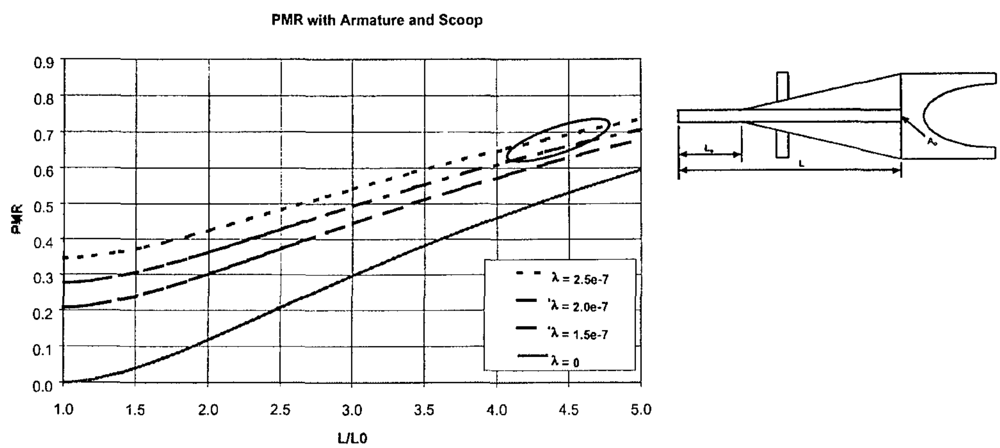


FIGURE 4 - FRP sabots - $\lambda = V/(L' \times g)$ in SI units

Figures 3 and 4 depict the variation in PMR as a function of L/L_0 for base-push EM projectiles with tungsten alloy penetrators having aluminium and FRP sabots respectively.

The analysis is the same as presented in Fig 2 except that the masses of an air-scoop (front bore-rider) and an armature are now included. It is additionally assumed that:

- An appropriate size of gun is available, and that together with its power supply, the system will enable the chosen acceleration and velocity combination to be realised.
- The air-scoop is assumed to have the same diameter as the base of the sabot.

The armature mass has been estimated by first evaluating

$$A_A^2 = \frac{2M_S V}{L' g} \tag{1}$$

where A_A is the minimum current carrying cross-sectional area of the armature assuming a uniform current distribution, M_S is the total shot mass, V is the muzzle velocity, L' is the barrel inductance gradient and g is the specific action for the armature material. The specific action for various armature alloys has been evaluated from

$$g = \frac{\rho\, C_P}{\varepsilon} dT \tag{2}$$

where C_p is the specific heat, ρ is the density and ε is the electrical resistivity. In Eq (2), ε and C_p are taken as functions of temperature. Values of C_p for pure aluminium and a range of aluminium alloys have been determined by DERA from room temperature up to melt, and beyond, by experiment. The correlation between A_A and the armature mass is determined from limit-case EM gun firings at both 40mm calibre and 90mm calibre.

Usually the bore of the gun would be slightly larger than the sabot base size. The error involved in estimating the scoop mass using the sabot base diameter is considered small because the annulus between the scoop and the bore would be mostly filled with a lightweight insulating material, typically a suitable grade of nylon.

As before, PMR is a function of L/L_0, but now the parameter $\lambda = V/L'g$ is included to size the armature. A range of λ values have been included to cover typical combinations of V, L' and g. The special case of $\lambda = 0$ corresponds to a base-push shot without an armature and should be compared with the corresponding result in Fig 2 to assess the effect of the mass of the air scoop on PMR. Also of interest are the intercepts at the y-axis for the various λ values. Here, PMR_0 values can be obtained for projectiles comprising rods of length $L = L_0$ and their armatures, but which do not require sabots.

The mass of an armature typically adds ~0.1 to the PMR of aluminium sabotted shot at a sensible value of L/L_0 (ie ~ 4). The effect is more pronounced for FRP sabotted shots where the PMR is increased by ~0.15 at $L/L_0 = 4$ by including the armature. Inspection of Fig 3 shows that a PMR of 0.5 is only possible with aluminium alloy sabotted rounds if very short rods are considered. At a PMR of 0.5, lightweight FRP sabots can (theoretically) increase L/L_0 by about a third compared to an aluminium alloy sabotted projectile. The relationships depicted in Figs 3 and 4 are not exact (finite element analysis of designs would provide a better answer), but do indicate the correct trends, namely that it is very difficult to achieve respectable PMRs for base-push EM shots, and that the mass of the armature is significant in this respect.

Achieving hypervelocity with the same length barrel as a conventional gun increases the duration of the accelerating forces. The laminated, 90mm calibre, International Applied Physics (IAP) laboratory gun at Kirkcudbright was found to impart severe balloting (lateral acceleration) loads to projectiles as they travelled along the barrel under the extended action of the acceleration force combined with increased velocity (Ref 2). Thus additional parasitic mass over conventionally fired, ordnance velocity, projectiles is required for two reasons: the mass of driving armature behind projectile; and the higher transverse balloting forces. The latter is not reflected in the theoretical treatment of Figs 3 and 4 but is usually manifested in the need for a shorter front overhang, less than the L_0 required to otherwise size the sabot.

Armature Development

The development of low-mass armatures with improved electrical performance has always been recognised as a key factor in the success of EM gun technology. Early UK base-push armature designs were of the C-shape type, weighing some 1.2kg at 90mm calibre. As expertise grew, aided by the unique capability at Kirkcudbright to recover fired armatures, this mass was reduced to approximately 0.8kg. Further mass reductions were demonstrated but at the expense of earlier transition. Typical engineering weight-saving measures such as drilling holes, tapering dimensions and chamfering corners were all tried with mixed success.

In the light of this, the UK MoD has funded a dedicated research programme covering armature materials. The technical approach has been to combine the mechanical properties sought with the possibility of manufacturing armatures having preferential current flow to minimise ohmic heating in critical regions. The programme included the development of methods for characterising mechanical, electrical and thermal properties of candidate armature materials subjected to launch-type conditions, together with thermo-electromagnetic modelling of armatures and the development of a micro-mechanics design code to predict anisotropic electrical properties. The four key areas of investigation have been:

- Joining of dissimilar metals.
- Dispersion hardened and particulate reinforced metal matrix components.
- Continuous fibre reinforced metal matrix components.
- Porous refractory metals.

Multi-material armatures are perceived to offer the advantages associated with tailored thermal and electrical properties and several examples have been fired successfully.

EM GUN PROJECTILES - BASE-PUSH

The UK commenced large calibre EM gun research with an extensive history in round-bore conventional guns and projectiles. This background, coupled with the fact that the US had already amassed a database of 90mm calibre EM launch packages, led to the choice of 90mm round-bore as the preferred calibre type.

The UK EM launch packages are designated by the 'U' series nomenclature. The early designs were base-pushed and used a 'C' shaped armature of aluminium alloy to drive the shot from behind. Whilst this configuration is not particularly mass efficient, it was chosen to allow independent development of shot and armature. Some of the packages feature fibre reinforced plastic sabots; the remainder using high strength aluminium alloy. The high specific strength and stiffness of FRP is well known and translates in this application to a lower parasitic mass. Thus for a given launch energy, faster and/or heavier penetrators can be fired with an FRP sabot compared to an aluminium alloy one.

The velocity regimes for the first three 90mm round-bore EM projectiles U1, U2 and U3 were all above $2000ms^{-1}$. The shot mass constraints implied by the 32MJ capacitor bank immediately made the use of lightweight FRP sabots mandatory for the higher velocity rounds U1 and U2.

The aluminium alloy sabotted U3, and its fin-stabilised variant U4, have been used to successfully demonstrate strength of design and repeatability when fired from the IAP barrel at Kirkcudbright and the Task B gun at Green Farm (Ref 7). The PMR for U4 is high at 0.78, but the use of composite sabots permits lower PMRs and longer rods to be fired at tactical velocity.

The second generation of UK lightweight EM gun projectiles, U7 and U9, were similar to U2 and U1 respectively, but used alternative manufacturing methods for the FRP sabots.

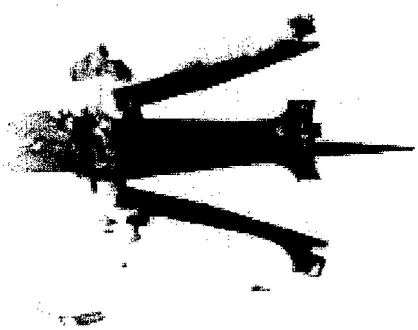
All of the above FRP sabotted designs have flare stabilised sub-projectiles. The third generation of lightweight EM shots, represented by U10, was typified by longer rods and the move towards fin stabilisation.

All UK base-push projectiles are first tested for strength of design in powder gun firings to axial accelerations well in excess of what is required for a hypervelocity launch from an EM gun. Clearly, it was not possible with powder guns to test both peak accelerations and required velocities at the same time.

Of particular note are the EM gun firings at the US Green Farm facility of U7 and U9 (Fig 5) at velocities considerably in excess of $2000ms^{-1}$ - including the fastest launch of a tactical KE launch package.

Bore straightness and stability under firing loads have long been recognised as poor in existing EM launchers when compared with conventional powder guns. A major consequence is that lateral accelerations (ie balloting forces) are thought to be some five to 10 times higher during an EM launch than those experienced during a conventional powder gun firing. The bore of the 90mm IAP barrel at Kirkcudbright is not particularly straight or round and the bore shape changes with each shot (although considerable improvements have been made to this barrel recently, Ref 2). Both the U7 and U9 projectiles have suffered nose tip failures when fired from the IAP barrel, a failure mode noted by other researchers (Ref 8).

The lowest shot parasitic mass achieved to date for a base-push launch package was 0.66 for the U10v2 projectile with FRP sabot and mid-length penetrator. This design has been launched successfully to its design acceleration from a conventional gun, and is awaiting an appropriate quality of EM barrel before it is fired. Obviously lower parasitic mass values can be achieved for lower accelerations and shorter penetrators. The rod size in U10v2 was chosen as being the optimum to achieve the best penetration for a given breech energy, bore size and sub-projectile diameter. Figure 6 shows EM projectiles U7, U9, U10v1 and U10v2 together with their parasitic mass ratios (calculated including armatures). It should be noted that the rounds pictured have a wide range of penetrator lengths and different muzzle velocities, yet the PMRs are in a relatively tight band from 0.66 to 0.74.



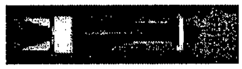
Projectile	PMR	
U7	0.74	
U9	0.69	
U10v1	0.70	
U10v2	0.66	

FIGURE 5 FIGURE 6

The parasitic mass ratio of base-push projectiles remained high, even with composite sabots, and a move towards mid-ride concepts was made. Again, the knowledge accumulated from conventional gun firings of double-ramp sabotted rounds was used to good effect.

EM GUN PROJECTILES - MID-RIDE

Design Concepts

More mass efficient EM gun projectiles can be designed with a mid-ride configuration. Instead of the armature being at the back of the round, in a mid-ride shot the armature is positioned part-way along the sabot so that some of the penetrator is towed behind the shot in tension. This shape is similar to a double-ramp sabot configuration sometimes used in conventional projectiles eg US M829 A2.

Three types of mid-ride sabot construction can be envisaged:

- All-metallic with combined sabot/armature functionality.
- An all-metal concept with selective FRP reinforcement introduced into regions where high electrical conductivity is not required.
- An FRP sabot with integrated metallic armature.

Examples of all three types have been investigated to assess their parasitic mass ratios and the most promising schemes have been analysed fully by finite element analysis to check for strength of design. All of the design schemes are for a conventional two-rail launcher and feature at least one split line in the sabot/armature aligned with the rail-to-rail centre line.

The best parasitic mass ratio for a shot with a mid-range L/D rod is estimated as 0.58, achieved using an FRP sabot. This is an improvement on base-push designs, but (assuming that the proposed scheme would be successful) is still some way from reaching the goal of PMR = 0.5. The key to reducing parasitic mass further is to understand how the armature can be made lighter and this requires extensive thermo-electromagnetic and structural modelling using the finite element method.

The most efficient mid-ride projectile scheme proposed (0.58 parasitic mass ratio) requires the parasitic mass to be reduced by a further 27% before the PMR = 0.5 goal can be achieved. Even with a mid-ride design this is clearly a difficult goal to meet given the present rod length, rod diameter and acceleration specification. Increasing the rod diameter, reducing the rod length and reducing the launch acceleration would simplify this task. These decisions are critically dependent on the ability to model the overall system trade-offs (Ref 9).

Firing Trials

Experiments to date have examined all-metallic, mid-ride constructions. U13 and U14 are aluminium alloy sabotted mid-ride designs with integral armatures, the former being a development proof shot, the latter being a fully functioning APFSDS shot.

The proof shot projectile designated U13v1 was developed to examine the erosion and magnetic effects on parts of the penetrator and fin which extend into the plasma environment between the armature legs. This one-piece proof shot with integral armature and trailing core section enables a variety of fin materials to be fired and recovered intact for technical analysis. U13v2 is a split design having two aluminium alloy sabot petals enabling integral armature performance and sabot discard to be assessed. Further development has led to the U14 (Fig 7), a full APFSDS shot, which represents the first practical step in the UK towards an EM gun-launched, mid-ride projectile. The parasitic mass ratio of this projectile is at present 0.68 which is comparable to the FRP sabotted, base-push U10v2 (albeit U14 is not designed to equivalent acceleration levels).

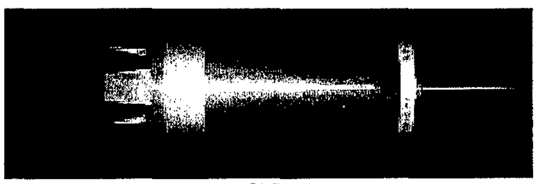


FIGURE 7

Mid-Ride Armature Development

All of the FRP sabotted mid-ride concepts described above feature armatures with a central, longitudinal hole to allow the rear sabot ramp section to pass through. The presence of a hole in the armature reduces its strength and current carrying capacity.

Figure 8 shows the result of 3D EM modelling of a standard armature and one modified with a central hole at peak current during a 1.5MA current pulse. Contours of specific action, relative to the specific action for the armature material, have been calculated on the diametral plane of minimum cross-section (Fig 9).

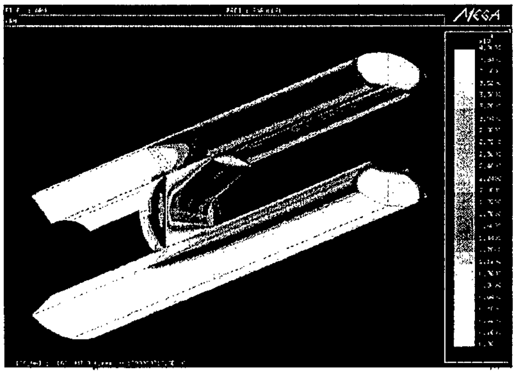


FIGURE 8A: Armature without central hole

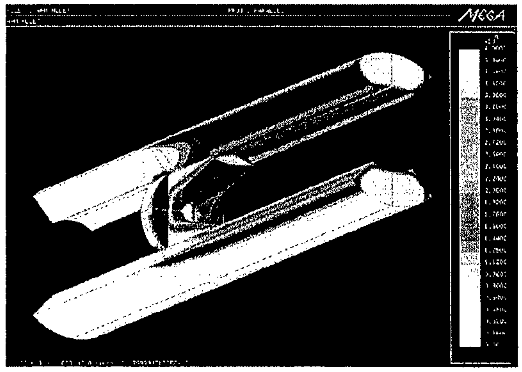


FIGURE 8B Armature with a central hole

The standard armature has a 'specific action concentration factor' of 5.1 compared to 6.9 for the armature with the central hole, both relative to the specific action assuming a uniform current distribution,

$$g = \left(\frac{I}{A_A}\right)^2 dt \qquad (3)$$

where I is the input current.

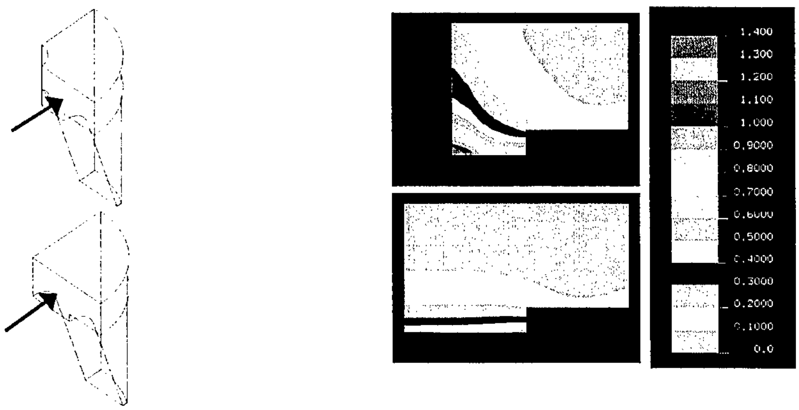


FIGURE 9

Armatures containing central longitudinal holes of various diameters have been fired at representative action levels. Providing that the hole was not too large, the effect on performance was minimal, though at higher velocities and energies the armatures tended to split in two and distort under the large internal magnetic forces present in the armature.

Figure 10 shows the effect of the action concentration around the hole on a recovered armature - visible microstructural changes in regions where the specific action of the armature material has been exceeded correlate well with the EM modelling for a comparable current pulse (Fig 9).

A more realistic mid-ride style armature was fired containing a tapered glass reinforced plastic plug representing the sabot. Although the armature was fired as a base-push design behind a U9 proof-shot, the amount of armature material removed is representative of the FRP sabotted mid-ride designs discussed above. The recovered armature is shown in Fig 11 having been successfully fired at 1500ms^{-1}. Clearly there is still some way to go to reach hypervelocity and it is thought that a similar, yet multi-material, design might provide a solution.

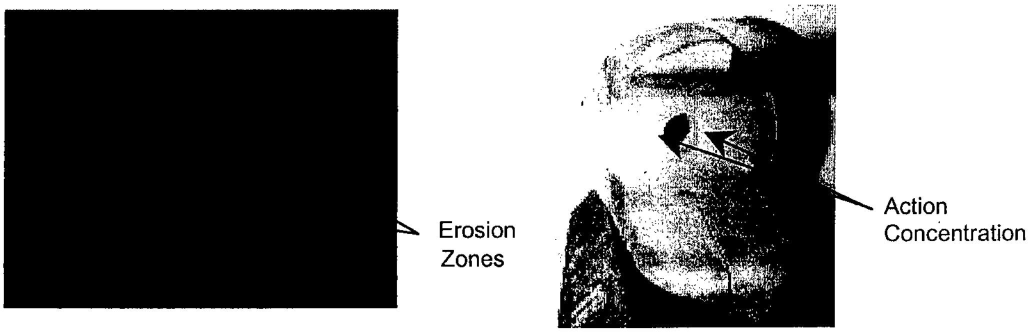


FIGURE 10

FIGURE 11

The EM armature modelling and firing trials are being used to gain a better understanding of the relationship between A_A from Eq (1) and the dimensions of functional armatures.

EM GUN PROJECTILES - BORE SHAPE

Circular (ie round) bores were chosen initially for compatibility with existing powder gun design methodologies and with previous US work. With base-push projectile designs, round-bores work well, and transition velocities over 2000ms^{-1} can be achieved. However, with mid-ride concepts, round-bore armatures have restricted space for a trailing penetrator scheme to work properly. Selecting a rectangular geometry may improve this situation as well as increasing the barrel inductance gradient (relative to a round-bore) to reduce the electrical load into the armature. Also the current distribution across the rail from edge-to-edge is more uniform, reducing the severity of the concentration at the rail corners.

Analysing and manufacturing bore shapes other than round presents further challenges to the projectile community. Numerical models become much more complicated and fully 3D analyses are essential. Simple rectangular-bore barrel designs can be manufactured, though final surface finishing is not as easy as for round-bores. If there is a requirement to move to some form of elliptical or combined flat/round-bore shape (Ref 2), then serious consideration would have to be given to the production of such shapes, regardless of their potential paper benefits.

Figure 12 shows that an elliptical cross-section sabot, assuming an isotropic sabot material, is as effective at controlling rod stress as a sabot of circular cross-section whilst maintaining the same PMR. This finite element analysis suggests that the PMR relationships in Fig 2 still hold for mildly non-circular, aluminium alloy sabot cross-sections.

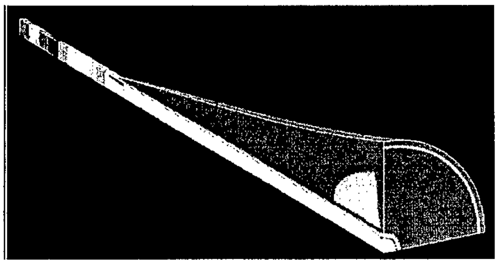


FIGURE 12A: ¼ model circular sabots

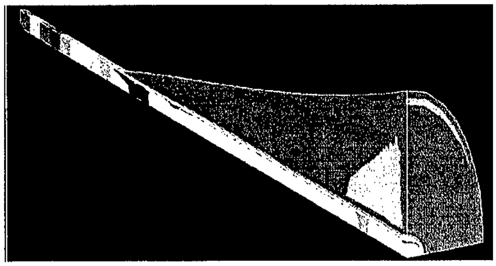


FIGURE 12B: ¼ model elliptical sabots

An elliptical cross-section sabot is not an unreasonable choice for a rectangular-bore barrel providing a natural transition between the bore and the circular cross-section penetrator. Elliptical flight bodies also offer some potential from the aerodynamic viewpoint. With non-circular sabots, careful consideration must be given to the unusual shear stress distribution arising from the non-axisymmetric sectional stiffness; this may cause problems with some anisotropic composite materials.

CONCLUSIONS AND NEXT STEPS

This paper has illustrated the complexities associated with the development of EM projectiles for the direct-fire KE application. A number of important lessons can be learned:

- EM projectiles cannot compete with conventional projectiles in terms of parasitic mass ratio, given present understanding. It will be a major challenge to achieve a parasitic mass ratio of less than 0.58 for a round-bore EM launch package containing a meaningful L/D penetrator.
- Moving to a more oblate bore cross-section (eg extended oval, elliptical) offers a potential advantage in PMR, in that the L' of the gun is increased and the armature needs to carry less electrical energy. Alternate aerodynamic flight bodies become possible within such envelopes, but at the expense of greater complexity in manufacture of both launcher and projectile.
- Within the UK, the ability to recover fired armatures has contributed significantly to an improved understanding of the fundamental physics being employed, and in the development of thermo-electromagnetic modelling tools with greater fidelity. Good progress has been made in this direction, though further improvements will aid the evolution of launch packages which may prove intractable otherwise.

- The armature/sabot materials and launch package geometry technologies are a long way from maturity and there is a need (and every likelihood) of some significant breakthroughs before a formal commitment to the development and procurement of an EM weapon system is initiated.

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REFERENCES

1. Robert J. Taylor, "Influence of Combat Vehicle System Constraints on EML Technology Development," *IEEE Transactions of Magnetics, Vol 35, No. 1,* 473-478, January 1999
2. M. J. Hinton, A. Howard, N. R. Cooper, D. K. Wallington and M. A. Firth, "Concepts for Fieldable Electromagnetic Gun Barrels, to be presented at " *10th U.S. Army Gun Dynamics Symposium, P42,* 23-26 April 2001
3. David Haugh, "An Update on the UK Electric Gun Research Programme," *IEEE Transactions of Magnetics, Vol 33, No. 1,* 17-20, January 1997
4. Doug Kirkpatrick and David Haugh, "Launching Tactically Configured Solid Armature Projectiles from Large and Medium Calibre Railguns - Results from the DRA Test Programme," *IEEE Transactions of Magnetics, Vol 33, No. 1,* 109-114, January 1997
5. Alexander E. Zielinski and Paul Weinacht, "Improved Integrated Launch Package Ballistic Performance," *IEEE Transactions of Magnetics, Vol 35, No. 1,* 124-129, January 1999
6. B. Burns, L. Burton and W. Drysdale, "Methodologies for Forecasting Sabot Mass for Advanced Gun and Projectile Systems," *Ballistics Research Laboratory Report, BRL-TR-3387,* September 1992
7. David Haugh and Doug Kirkpatrick, "Large Calibre Armature Firings at Green Farm Electric Gun Test Facility," *IEEE Transactions of Magnetics, Vol 33, No. 1,* 68-73, January 1997
8. Timothy E. Hayden, Rolf Dethlefsen and John H. Price, "Effective Launch Package Integration for Electromagnetic Guns," *IEEE Transactions of Magnetics, Vol 31, No. 1,* 150-155, January 1995
9. Scott Fish, Todd McGall and Erik Howard, "Launch Package Mass and Pulsed Power Energy Estimation for Subcalibre Electromagnetic Railgun Projectiles," *IEEE Transactions of Magnetics, Vol 33, No. 1,* 63-67, January 1997